

Weak and Electromagnetic Nuclear Decay Signatures for Neutrino Reactions in SuperKamiokande

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We suggest the study of events in the SuperKamiokande neutrino data due to charged- and neutral-current neutrino reactions followed by weak and/or electromagnetic decays of struck nuclei and fragments thereof. This study could improve the prospects of obtaining evidence for τ production from $\nu_\mu \rightarrow \nu_\tau$ oscillations and could augment the data sample used to disfavor $\nu_\mu \rightarrow \nu_{sterile}$ oscillations.

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The very large SuperKamiokande (SK) underground water Cherenkov detector has contributed greatly to our knowledge of solar and atmospheric neutrino physics [1–4], as well as yielding stringent limits on nucleon decay [5]. The atmospheric data has, with high statistics, provided evidence for neutrino oscillations and hence neutrino masses and lepton mixing; the best fit is to $\nu_\mu \rightarrow \nu_\tau$, with $\Delta m_{atm}^2 \sim 3.5 \times 10^{-3} \text{ eV}^2$ and maximal mixing, $\sin^2 2\theta_{atm} = 1$ [3]. These values are also consistent with data from the Soudan-2 [6] and MACRO [7] experiments, as well as the K2K long baseline experiment [8]. SK has also obtained a large sample of solar neutrino events, yielding a confirmation of a factor of 2 deficit relative to calculations, measurement of the energy distribution, and tests of day-night asymmetry and seasonal variation.

The main neutrino reactions that have been analyzed in SK include, for solar neutrinos, $\nu_e e$ elastic scattering and, for atmospheric neutrinos, quasi-elastic charged-current (CC) scattering, $\nu_\ell + n \rightarrow \ell^- + p$, $\bar{\nu}_\ell + p \rightarrow \ell^+ + n$, where $\ell = e, \mu$ [3], and neutrino-induced single and multi-pion production [4]. These all involve prompt particle production. However, because the primary neutrino reactions can lead to excited levels of nuclei or to nuclei with unstable ground states (g.s.), γ and delayed β and $\beta\gamma$ decays can occur in conjunction with these primary neutrino reactions and the hadronic cascade which may accompany them. This is particularly true of atmospheric neutrinos because their energies extend to $\sim \text{GeV}$, as contrasted with the 14.5 MeV upper end of the solar ^8B ν_e 's. When the released energy from these decays exceeds about 5-6 MeV, they should be detectable. Indeed, SK has successfully measured scattered electrons with energies of 5 MeV in their solar neutrino data sample, despite the backgrounds that become increasingly severe at low energies [1,2]. Here we suggest the study of these events and analyze some of their signatures. In 1144 days of running, SK has obtained 9178 atmospheric neutrino events that are fully contained (FC) in the 22.5 kton fiducial part of the 50 kton total volume [3,4]; from this it has been estimated that SK should have approximately 70 events involving charged-current τ^\pm production by ν_τ and $\bar{\nu}_\tau$ originating from the inferred $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ oscillations [3]. The additional information that the γ , β and $\beta\gamma$ decays provide could improve the understanding of both single-ring and multi-ring events, helping the efforts to pick out these τ^\pm events.

Many of the primary charged- and neutral-current (CC and NC) neutrino interactions, as well as secondary interactions of pions, nucleons, and possibly larger nuclear fragments, occur on the ^{16}O nuclei. These interactions can involve charge exchange, further emission of one or more nucleons, breakups into fragments, and excitations that promptly decay via nucleon emission. In many of these cases, these process leave unstable nuclei at the locations (vertices) of the original neutrino reactions. These nuclei may have been excited to higher levels that decay electromagnetically to the respective ground states promptly via

photon emission. Such decays coincide, to within the experimental time resolution of the SK detector, with the initial event and yield monochromatic γ 's. There can occur ground states of nuclei (Z, A) that subsequently beta decay to neighboring nuclei ($Z \pm 1, A$). For several nuclei with $A \leq 16$, the maximum e^\pm energies, i.e., Q_β values, exceed the expected 5-6 MeV threshold for detection above background. The lifetimes of these beta decays range between ~ 0.01 sec and 10 sec, well beyond the time window of the original event. Hence these beta decays occur during a time when the original Cherenkov signals from the primary reaction have ceased, and therefore would not be confused with them. The same struck oxygen nucleus will serve as the origin for the Cherenkov cone associated with the delayed β (and *a fortiori* any prompt γ) and one or several cones in the initial neutrino event and its associated hadronic cascade. The beta decay times are short enough to prevent any significant motion of the radioactive nuclei away from the location of the primary vertex due to the momentum transfer in the primary neutrino reaction or the motion of the water owing to its recirculation (at a rate of 50 tons/hour [9]). The recoil of the nucleus or fragment in question is of order the Fermi momentum $p_F \sim 300$ MeV/c (larger momentum transfers typically result in further fragmentation); hence the range of this nucleus is much shorter than the spatial resolution with which the location of the primary event vertex can be reconstructed. This spatial resolution depends on the angle with respect to the Cherenkov cone and with the lepton energy [3]; here, to be conservative in our background estimates, we shall take it to be 1 m.

Accidental backgrounds are negligible for the cases of decays of excited nuclei by prompt photon emission, since these are simultaneous, to detector time resolution, with the initial event. Next consider beta decays. From the 9178 fully contained atmospheric neutrino events in 1144 days, it follows that these events occur at an average rate of 0.33 per hour. The key discriminant here is that the Cherenkov cones or showers associated with the delayed β and/or $\beta\gamma$ decays must originate from a volume of ~ 1 m³ out of the 2.25×10^4 m³ fiducial volume. Over a time window after the primary reaction of 30 sec, say, accidental background events of this type should therefore be negligible. A particular background arises from decays of nuclei that are spallation products of collisions of through-going muons. These were also a background for the solar neutrino signal and were effectively removed by rejecting events in which a beta emerges from a cylindrical region around the path of the through-going muon during a time from msec to O(10) sec after this muon traverses the detector [1,2,10]. The same method could be used here. An additional check on backgrounds is obtained from the SK data on e -type single-ring solar neutrino events as a function of angle with respect to the sun, $\cos \theta_{sun}$ [1]. This data showed a background, of ~ 0.09 events/day/kton/bin, isotropic in $\cos \theta_{sun}$ (and the solar neutrino signal above it, at $\cos \theta_{sun} \simeq 1$); this number yields, in 1 m³ volume, over a 30 sec time window, a negligibly small rate for this background. Having

outlined the general idea, we proceed to specific cases.

As a first example for atmospheric neutrinos, consider the reaction

$$\bar{\nu}_\ell + {}^{16}\text{O} \rightarrow \ell^+ + {}^{16}\text{N} \quad (1)$$

where $\ell = e$ or μ . The g.s. of the ${}^{16}\text{N}$ nucleus beta decays, with half-life $t_{1/2} = 7.1$ sec, to various levels of ${}^{16}\text{O}$, primarily the g.s., with branching ratio $BR = 26$ % and maximum e^- energy $Q_\beta = 10.42$ MeV, and the 3^- state, with $BR = 68$ % and $Q_\beta = 4.29$ MeV, which then decays promptly (in 18 psec) to the g.s. via emission of a monochromatic 6.13 MeV photon (this and other nuclear properties are from [11]). The selection criteria for these events would be (i) fully contained (FC) within the 22.5 kton fiducial volume, with (ii) a Cherenkov ring from the initial ℓ^+ , (iii) for $\ell^+ = \mu^+$, a second, e^- -type ring from the μ^+ decay, (iv) in a timing window of $0 \leq t \leq 30$ sec after the initial signal the appearance of an e^- with a reasonable fraction of 10.4 MeV, from the direct decay, or a 6.13 MeV γ from the branched decay, satisfying the requirement that (v) the e^- Cherenkov showering cone or the shower from the γ extrapolate back to the vertex reconstructed from the initial ℓ^+ Cherenkov signal. Note that SK has achieved an accuracy of better than 1 % in the energy scale and about 15 % in $\Delta E/E$ for 10 MeV electrons in its solar neutrino data [1,2]. Some relevant cross section calculations for the primary atmospheric neutrino reactions are [12], [13]. For a rough estimate of the fraction of the reactions (1) that yield ${}^{16}\text{N}_{g.s.}$, we may refer to the CRPA (continuous random phase approximation) calculations of analogous CC neutrino reactions on ${}^{12}\text{C}$ [14] (see also [15], [16]) performed to compare with LSND data [17]. It was found that reactions yielding nuclides close to the valley of beta stability occurred with sizable fractions of the inclusive yield; e.g., the flux-averaged cross sections for ${}^{12}\text{C}(\bar{\nu}_\mu, \mu^+){}^{12}\text{B}_{g.s.}$ and ${}^{12}\text{C}(\bar{\nu}_\mu, \mu^+n){}^{11}\text{B}_{g.s.}$ comprised, respectively, 6 % and of 34 % of the inclusive process ${}^{12}\text{C}(\bar{\nu}_\mu, \mu^+)X$. From these, we estimate that the atmospheric neutrino flux-averaged cross section for ${}^{16}\text{O}(\bar{\nu}_\ell, \ell^+){}^{16}\text{N}_{g.s.}$ could be $\sim O(10)$ % of ${}^{16}\text{O}(\bar{\nu}_\ell, \ell^+)X$. Using this ratio and the flux-averaged σ 's for $\bar{\nu}_\ell p \rightarrow \ell^+ n$ and ${}^{16}\text{O}(\bar{\nu}_\ell, \ell^+)X$ from [12], we estimate that of the 3107 e^- -like and 2988 μ^- -like single-ring FC events in the 1144 day SK data, there could be $O(10^2)$ events of type (1) leading to ${}^{16}\text{N}_{g.s.}$, of which about 40 % would have $E_e > 6$ MeV.

Another pathway for producing ${}^{16}\text{N}$ is a regular fully contained event $\nu_\mu n \rightarrow \mu^- p$ where the μ^- is captured on another oxygen nucleus via ${}^{16}\text{O}(\mu^-, \nu_\mu){}^{16}\text{N}$, followed by the beta decay of the ${}^{16}\text{N}$. Such an event can be distinguished from those which we propose to study because for typical E_μ , the μ^- travels sufficiently far from the primary event vertex that criterion (v) above would not be satisfied; for example, the μ^- range $R \sim 2$ m for $p_\mu = 500$ MeV/c. We note that SK has been able to measure beta decays of ${}^{16}\text{N}$ nuclei produced

both artificially, by the $^{16}\text{O}(n, p)^{16}\text{N}$ reaction, and naturally, by stopping μ^- 's captured on ^{16}O [18]. In 1004 days of data, a rate of 11.4 ± 0.2 events/day from the $^{16}\text{O}(\mu^-, \nu_\mu)^{16}\text{N}$ reaction and subsequent ^{16}N beta decay in an inner 11.5 kton fiducial volume was measured, in agreement with a prediction of 11.9 ± 1.0 events/day. Note that SK, in its search for the nucleon decay $p \rightarrow \bar{\nu} K^+$, used as an event criterion the observation of a 6.32 MeV photon from a resultant excited ^{15}N nucleus [5].

Neutrino reactions can lead to the fragmentation of the ^{16}O nucleus with emission of protons, neutrons, and higher- A fragments. For example, consider

$$\bar{\nu}_\ell + ^{16}\text{O} \rightarrow \ell^+ + p + ^{15}\text{C} . \quad (2)$$

The g.s. of ^{15}C beta decays, with $t_{1/2} = 2.4$ sec, to (i) the g.s. of ^{15}N , with $Q_\beta = 9.77$ MeV, $BR = 32$ %, and (ii) the 5.30 MeV level, with $Q_\beta = 4.47$ MeV, $BR = 68$ %, followed promptly by decay to the g.s. with emission of a 5.30 MeV photon. Although the branched decay would be difficult to detect, the energy of the e^- could be large enough to detect.

Higher- A fragmentation reactions include

$$\bar{\nu}_\ell + ^{16}\text{O} \rightarrow \ell^+ + ^3\text{He} + ^{13}\text{B} . \quad (3)$$

The ^{13}B nucleus beta decays with $t_{1/2} = 17$ msec, mainly ($BR = 93$ %) to the g.s. of ^{13}C , emitting an e^- with $Q_\beta = 13.4$ MeV. A second example is

$$\bar{\nu}_\ell + ^{16}\text{O} \rightarrow \ell^+ + ^4\text{He} + ^{12}\text{B} . \quad (4)$$

Here the ^{12}B nucleus beta decays with $t_{1/2} = 20$ msec to several levels of ^{12}C , mainly ($BR = 97$ %) to the g.s. with $Q_\beta = 13.4$ MeV. A third case is

$$\nu_\ell + ^{16}\text{O} \rightarrow \ell^- + ^4\text{He} + ^{12}\text{N} \quad (5)$$

followed by the beta decay $^{12}\text{N} \rightarrow e^+ + \nu_e + ^{12}\text{C}$ with $t_{1/2} = 11$ msec, mainly ($BR = 94$ %) the g.s. with $Q_\beta = 16.3$ MeV. For a rough estimate of the cross sections for (4) and (5), we note that for the similar CC reactions on ^{12}C , the CRPA calculation of [14] found that the flux-averaged σ 's for $^{12}\text{C}(\nu_\mu, \mu^- \alpha)^8\text{B}$, $^{12}\text{C}(\nu_\mu, \mu^- p \alpha)^7\text{Be}$, $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ \alpha)^8\text{Li}$, and $^{12}\text{C}(\bar{\nu}_\mu, \mu^+ n \alpha)^7\text{Li}$ comprised 7.5 %, 18 %, 7.5 %, and 13 % of the respective inclusive reactions $^{12}\text{C}(\nu_\mu, \mu^-)X$ and $^{12}\text{C}(\bar{\nu}_\mu, \mu^+)X$. This suggests that, if comparable rates apply for (4) and (5), the current SK data could contain $O(10^2)$ events from these reactions, summed over e and μ type (anti)neutrinos, and 60 % (74 %) of the resultant ^{12}B (^{12}N) beta decays would yield e^\mp energies above 6 MeV.

There are also events of the form $^{16}\text{O}(\bar{\nu}_\ell, \ell^+)^{16}\text{N}^*$ in which the final state ^{16}N is in an excited state. Except for low-lying levels with excitation energies less than 0.4 MeV above the g.s., these decay promptly with neutron emission.

Among neutral-current reactions one has, for atmospheric neutrinos,

$$(\nu_\ell, \bar{\nu}_\ell) + ^{16}\text{O} \rightarrow (\nu_\ell, \bar{\nu}_\ell) + \pi^+ + ^{16}\text{N} . \quad (6)$$

The selection criteria for events of this type would be (i) FC, (ii) Cherenkov ring from the π^+ , (iii) observation of the β or $\beta\gamma$ decay of the ^{16}N , as described after (1). One could also look for the reactions

$$(\nu_\ell, \bar{\nu}_\ell) + ^{16}\text{O} \rightarrow (\nu_\ell, \bar{\nu}_\ell) + \pi^0 + ^{16}\text{O}^* \quad (7)$$

which populate excited states of the ^{16}O nucleus. Although the lowest excited state, at 6.05 MeV, is a 0^+ state and hence cannot decay to the 0^+ g.s. with the emission of a single photon, the 1^- state at 7.12 MeV decays promptly (in 8 fs) via an E1 transition, and one could try to detect the resultant photon. The selection criteria would be (i) FC, (ii) two photons with invariant mass $M_{\gamma\gamma} = m_{\pi^0}$, (iii) a third photon from the primary event vertex, to within experimental uncertainty, with $E_\gamma = 7.12$ MeV. Similar comments apply for electromagnetic decays from other excited states. This event selection could augment the sample of neutral-current (NC) events that might be used to disfavor further the $\nu_\mu \rightarrow \nu_{sterile}$ transition, strengthening the results of [4]. Although there is some uncertainty in theoretical model calculations of cross sections for NC pion production, and hence also of (6) and (7), direct measurements of neutrino-induced pion production in the K2K near detector [8] should ameliorate this problem.

Nucleons and pions emitted in primary reactions can lead to secondary ones, via $n + (Z, A) \rightarrow p + (Z-1, A)$, $p + (Z, A) \rightarrow n + (Z+1, A)$, and $\pi^\pm + (Z, A) \rightarrow \pi^0 + (Z\pm 1, A)$ charge-exchange processes. Other possibilities include (p, d) , (n, d) reactions, etc. The probability of excitation of any specific nuclear state in the primary (anti)neutrino-oxygen or secondary (pion or nucleon)-oxygen collisions may be low, and SK does not have 100 % efficiency for detecting the resulting, relatively low-energy γ , β , or $\beta\gamma$ signal. However, we are considering the *inclusive* rate for producing the (g.s. or excited state) of a nucleus with the requisite γ , β , or $\beta\gamma$ decay. Just as the many exclusive neutrino reactions sum up to yield a linearly rising inclusive neutrino cross section for energies beyond ~ 1 GeV, so also, the sum of the specific exclusive reactions considered here, leading to nuclear states that decay by γ , β , or $\beta\gamma$ emission, should be a significant fraction of the total. We note further that in a generic high-energy neutrino event or when a τ^\pm is produced and decays, there is substantial probability for one or more pions to be emitted. There can thus be a resultant hadronic

cascade involving collisions with several oxygen nuclei, leading to nuclear states that decay via γ , β , or $\beta\gamma$ decays. Indeed, this tends to happen precisely in the complex, multi-ring events that are difficult to analyze and for which even partial additional information locating a particular emission vertex would be useful. As noted, the study of these reactions could thus aid in extracting τ 's in the atmospheric data.

Similar comments can be made about neutrino reactions on ^{12}C , the nucleus (in addition to H) in a liquid scintillator. Indeed, as part of the selection criteria for $^{12}\text{C}(\nu_\ell, \ell^-)^{12}\text{N}_{g.s.}$ events, the LSND experiment included detection of the e^+ from the beta decay $^{12}\text{N} \rightarrow e^+ + \nu_e + ^{12}\text{C}$ ($t_{1/2} = 11$ msec). The mini-BooNE experiment at Fermilab will also measure the CC ν_μ reaction on carbon.

In the solar neutrino data, there is the NC reaction

$$\nu_e + ^{16}\text{O} \rightarrow \nu_e + ^{16}\text{O}^* \quad (8)$$

producing an excited state of ^{16}O . In contrast to the case with atmospheric neutrinos, here the transitions to the excited states are somewhat suppressed since much of the ^8B ν_e flux is below threshold. The 0^+ state at 6.05 MeV (reached via an allowed $0^+ \rightarrow 0^+$ Fermi transition) does not decay via single photon emission. The other low-lying excited states, e.g. the 1^- level at 7.12 MeV, require higher- L transitions from the 0^+ g.s. of ^{16}O . Neutral current neutrino-nucleus reactions on nuclei as means of observing solar and supernova neutrinos have also been discussed in [20,21].

In future work it would be worthwhile to carry out a unified Monte Carlo simulation with joint particle-nuclear inputs of the numerous nuclear production and decay pathways. In general, complicated phenomena can be better understood when viewed with a variety of wavelengths and/or times. Our discussion illustrates this [22]. Other examples include SN1987A seen via neutrinos [23] and in the optical, and gamma ray bursts seen with X-ray and via optical afterglows.

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